REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
08-02-2018	Final Report	1-May-2014 - 30-Oct-2017

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Final Report: Nonlinear Dynamics of Electroelastic Dielectric Elastomers	W911NF-14-1-0022
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611102
6. AUTHORS	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
Boston University Office of Sponsored Program 881 Commonwealth Avenue Boston, MA 02215 -1300	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 63905-EG.5

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Harold Park
UU	UU	UU	UU		19b. TELEPHONE NUMBER 617-353-4208

RPPR Final Report
as of 15-Feb-2018

Agency Code:

Proposal Number: 63905EG
Agreement Number: W911NF-14-1-0022

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DUNS Number: 049435266
EIN: 042103547
Report Date: 30-Jan-2018
Date Received: 08-Feb-2018
Final Report for Period Beginning 01-May-2014 and Ending 30-Oct-2017
Title: Nonlinear Dynamics of Electroelastic Dielectric Elastomers
Begin Performance Period: 01-May-2014
End Performance Period: 30-Oct-2017
Report Term: 0-Other

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 0
STEM Participants: 0

Major Goals: The proposed research will significantly advance the basic science and fundamental understanding of how rate-dependent material response couples to large, nonlinear material deformation under applied electrostatic loading to control the nonlinear dynamics and failure mechanisms of dielectric elastomers (DEs). We will also focus on exploring the exciting possibility of exploring and tuning the nonlinear dynamical behavior through a single parameter, i.e. the surface energy of the DE.

Accomplishments: 1. Demonstrated the significant effect that surface tension can have on the deformation of dielectric elastomers
2. Found that increasing surface tension, or equivalently the elastocapillary number, results in an increase in the critical voltage or electric field needed to nucleate an electromechanical instability in a dielectric elastomer
3. We have found, in agreement with recent experimental studies of constrained dielectric elastomer films, a transition in the surface instability mechanism depending on the elastocapillary number. In particular, a unique creasing to wrinkling surface instability was found as the elastocapillary number becomes larger than the film thickness
4. We demonstrated, using both nonlinear finite element simulations and a linear stability analysis, the emergence of an electro-elastocapillary Rayleigh-Plateau instability in dielectric elastomer (DE) films under 2D, plane strain conditions. When subject to an electric field, the DEs exhibit a buckling instability for small elastocapillary numbers. For larger elastocapillary numbers, the DEs instead exhibit the Rayleigh-plateau instability. The stability analysis demonstrates the critical effect of the electric field in causing the Rayleigh-plateau instability, which cannot be induced solely by surface tension in DE films. Overall, this work demonstrates the effects of geometry, boundary conditions, and multi-physical coupling on a new example of Rayleigh-Plateau instability in soft solids.
5. Uncovered the fact that the lowest order instability wavelength is an infinite wavelength, while finite wavelength Rayleigh-Plateau instability is observed for larger critical voltages.
6. One of the key challenges in modeling the nonlinear dynamical behavior of DEs is that all computational techniques to solve the coupled electromechanical system of equations for this class of materials have universally centered around a fully coupled monolithic formulation, in which the mechanical and electrostatic equations are solved simultaneously. Such monolithic formulations are accurate, but require significant computational expense, which has significantly hindered the ability to solve large scale, fully three-dimensional problems involving complex deformations and electromechanical instabilities of DEs. During this period, we have provided the theoretical basis for the effectiveness and accuracy of staggered explicit-implicit finite element formulations for DEs, where the mechanical and electrostatic equations are solved separately, while demonstrating the simplicity of the resulting staggered formulation. We have demonstrated the stability and accuracy of the staggered approach by solving complex electromechanically coupled problems involving electroactive polymers, where we focused on problems

involving electromechanical instabilities such as creasing, wrinkling, and bursting drops. In all examples, effectively identical results to the fully monolithic solution are obtained, showing the accuracy of the staggered approach at a significantly reduced computational cost.
7. We anticipate this development will be critical in enabling ARL personnel to easily and efficiently adapt their simulation codes to perform large-scale structural analyses of the dynamic behavior of DEs.

Training Opportunities: Supported the PhD studies of Saman Seifi, who began as a PhD student on this project starting January, 2015.

Results Dissemination: Journal Publications:
1. S. Seifi and H.S. Park. "Computational Modeling of Electro-Elasto-Capillary Phenomena in Dielectric Elastomers", International Journal of Solids and Structures 2016; 87:236-244.
2. S. Seifi and H.S. Park. "Electro-elastocapillary Rayleigh-Plateau Instability in Dielecric Elastomer Films", Soft Matter 2017; 13:4305-4310.
3. B. Osmani, S. Seifi, H.S. Park, V. Leung, T. Topper and B. Muller. "Nanomechanical Probing of Thin-Film Dielectric Elastomer Transducers", Applied Physics Letters 2017; 111:093104.
4. S. Seifi, K.C. Park and H.S. Park. "A Staggered Explicit-Implicit Finite Element Formulation for Electroactive Polymers", submitted to Computer Methods in Applied Mechanics and Engineering 2017.

University Presentations:
1. H.S. Park. "Computational Modeling of Electromechanical Instabilities in Dielectric Elastomers", Harvard University (Squishy Physics Seminar), August 2017.
2. H.S. Park. "Computational Modeling of Electromechanical Instabilities in Dielectric Elastomers", Xi'an Jiaotong University, China, May 2017.
3. H.S. Park. "Computational Modeling of Electromechanical Instabilities in Dielectric Elastomers", Massachusetts Institute of Technology, November 2016.
4. H.S. Park. "Computational Modeling of Electromechanical Instabilities in Dielectric Elastomers", Korea Advanced Institute for Science and Technology (KAIST), Korea, July 2016.
5. H.S. Park. "Computational Modeling of Electromechanical Instabilities in Dielectric Elastomers", Universite Paris-Est Marne-la-Vallee, Paris, May 2016.
6. H.S. Park. "Computational Modeling of Electromechanical Instabilities in Dielectric Elastomers", Harvard University, Cambridge, March 2016.
7. H.S. Park. "Computational Modeling of Electromechanical Instabilities in Dielectric Elastomers", Army Research Laboratory, Aberdeen, April 2015.

Conference Presentations:
1. H.S. Park and S. Seifi. "Computational Modeling of Electro-Elasto-Capillary Phenomena in Dielectric Elastomers", IMECE 2016, Phoenix, November 2016.
2. H.S. Park. "Computational Modeling of Electromechanical Instabilities in Dielectric Elastomers", SES 2016, College Park, October 2016 (Keynote Lecture).
3. H.S. Park and S. Seifi. "Computational Modeling of Electromechanical Instabilities in Dielectric Elastomers", WCCM 2016, Seoul, July 2016 (Keynote Lecture).
4. H.S. Park. "Computational Modeling of Electromechanical Instabilities in Dielectric Elastomers", SPIE EAPAD 2016, Las Vegas, March 2016.

Honors and Awards: " The PI (Park) was awarded the International Association for Computational Mechanics (IACM) John Argyris Award for Young Scientists in March 2016. This award is given once every two years to a single investigator 40 years or younger, and recognizes outstanding accomplishments, particularly outstanding published papers.
" PI Harold Park was named an ASME (American Society of Mechanical Engineers) Fellow for the class of 2016

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI

Participant: Harold Park
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Saman Seifi
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 4-Under Review
Journal: Computer Methods in Applied Mechanics and Engineering
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: Date Published:
Publication Location:
Article Title: A Staggered Explicit-Implicit Finite Element Formulation for Electroactive Polymers
Authors: Saman Seifi, K.C. Park, Harold S. Park
Keywords: staggered, dielectric elastomer, explicit-implicit
Abstract: Electroactive polymers such as dielectric elastomers (DEs) have attracted significant attention in recent years. Computational techniques to solve the coupled electromechanical system of equations for this class of materials have universally centered around fully coupled monolithic formulations, which while generating good accuracy requires significant computational expense. However, this has significantly hindered the ability to solve large scale, fully three-dimensional problems involving complex deformations and electromechanical instabilities of DEs. In this work, we provide theoretical basis for the effectiveness and accuracy of staggered explicit-implicit finite element formulations for this class of electromechanically coupled materials, and elicit the simplicity of the resulting staggered formulation. We demonstrate the stability and accuracy of the staggered approach by solving complex electromechanically coupled problems involving electroactive polymers, where we focus on
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Project Summary - Grant # W911NF-14-1-0022
(Reporting Period: May 2014 – October 2017)

Nonlinear Dynamics of Electroelastic Dielectric Elastomers

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Boston University, Boston, MA 02215

Objective

The proposed research will significantly advance the basic science and fundamental understanding of how rate-dependent material response couples to large, nonlinear material deformation under applied electrostatic loading to control the nonlinear dynamics and failure mechanisms of dielectric elastomers (DEs). We will also focus on exploring the exciting possibility of exploring and tuning the nonlinear dynamical behavior through a single parameter, i.e. the surface energy of the DE.

Approach

This objective will be accomplished by:

- Developing a nonlinear, coupled electromechanical displacement-pressure FEM formulation to enable fundamental studies of incompressible DE material behavior using standard low-dimensional FEs by eliminating any volumetric locking effects.
- Investigating surface tension effects on tailoring the nonlinear dynamics and electromechanical instability mechanisms of DEs.

Relevance to Army

The key source of the technological excitement surrounding dielectric elastomers (DEs) stems from the fact that if sandwiched between two compliant electrodes that apply voltage to the elastomer, the DE can exhibit both significant thinning and in-plane expansion. This unique large deformation-based actuation capability has led to many Army-relevant applications for DEs, including the potential to harvest energy from sources as diverse as human muscle motion and ocean waves, medical devices, and perhaps most importantly, artificial muscles.

More recently, various applications have been proposed based on DEs operating in fluidic environments. These include in situ magnetic resonance imaging (MRI), untethered underwater mobile systems, soft tunable lenses, soft body locomotion and the preparation of bio-inspired surfaces. All of these applications require the understanding of DEs in wet environments, where a fundamental understanding of the nonlinear dynamics of DEs in fluidic environments is currently lacking.

Accomplishments for Reporting Period

- Demonstrated the significant effect that surface tension can have on the deformation of dielectric elastomers. This is observed below in Figure 1, which shows a DE subject to voltage loading and varying amounts of surface tension. Figure 1(b) shows the deformation if no surface tension is present, while Figure 1(c) shows the deformation if surface tension resulting in an elastocapillary numer of 10 is present. As can be seen, if surface tension is present, as shown in Figure 1(c), the shape of the DE for the same amount of applied voltage is completely different: square instead of rectangular.

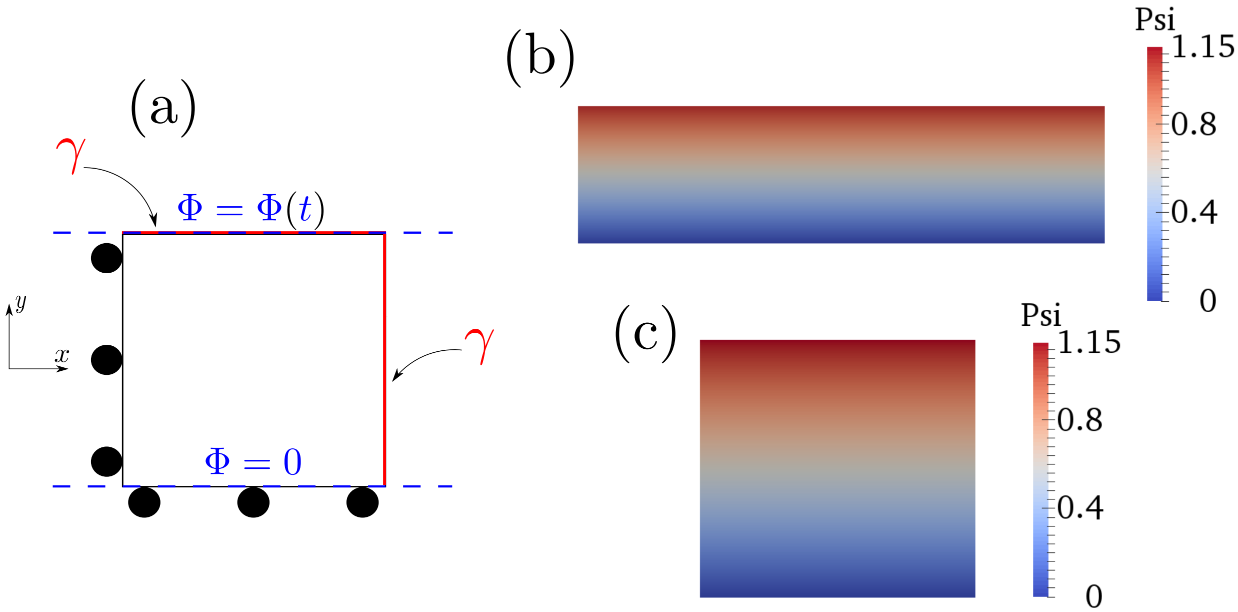

Figure 1: (a) Schematic of DE with homogeneous boundary conditions; (b) Deformed configuration for elastocapillary number of 0; (c) Deformation configuration with elastocapillary number of 10.

- Found that increasing surface tension, or equivalently the elastocapillary number, results in an increase in the critical voltage or electric field needed to nucleate an electromechanical instability in a dielectric elastomer. This is shown below in Figure 2, for the boundary condition shown above in Figure 1(a). Figure 2 shows the dramatic increase in critical voltage that occurs as the elastocapillary number increases.

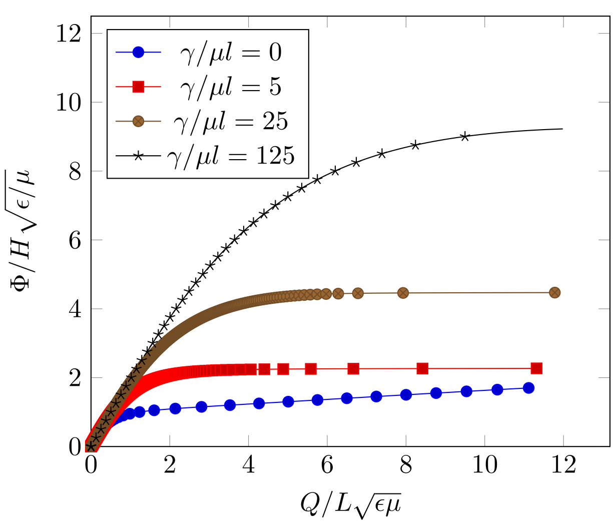

Figure 2: Homogeneous deformation of a DE subject to voltage loading for different elastocapillary numbers.

- We have found, in agreement with recent experimental studies of constrained dielectric elastomer films, a transition in the surface instability mechanism depending on the elastocapillary number. In particular, a unique creasing to wrinkling surface instability was found as the elastocapillary number becomes larger than the film thickness, as shown below in Figure 3.

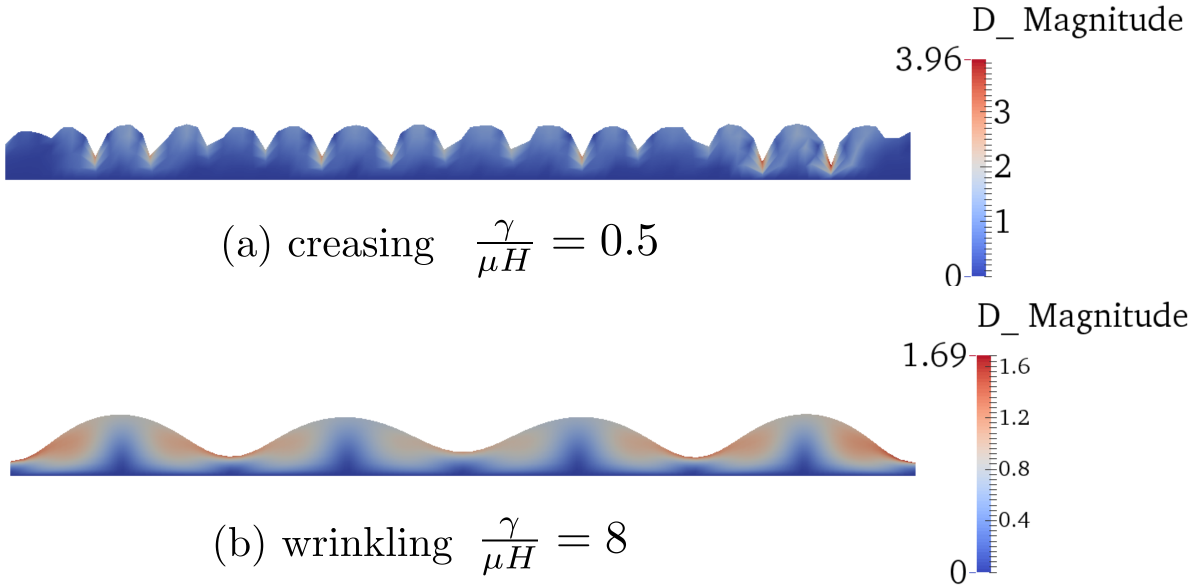

Figure 3: Computationally observed transition in the surface instability mechanism in DEs as a function of the elastocapillary length.

- We demonstrated, using both nonlinear finite element simulations and a linear stability analysis, the emergence of an electro-elastocapillary Rayleigh-Plateau instability in dielectric elastomer (DE) films under 2D, plane strain conditions, as summarized below in Figure 4. When subject to an electric field, the DEs exhibit a buckling instability for small elastocapillary numbers. For larger elastocapillary numbers, the DEs instead exhibit the Rayleigh-plateau instability. The stability analysis demonstrates the critical effect of the electric field in causing the Rayleigh-plateau instability, which cannot be induced solely by surface tension in DE films. Overall, this work demonstrates the effects of geometry, boundary conditions, and multi-physical coupling on a new example of Rayleigh-Plateau instability in soft solids.

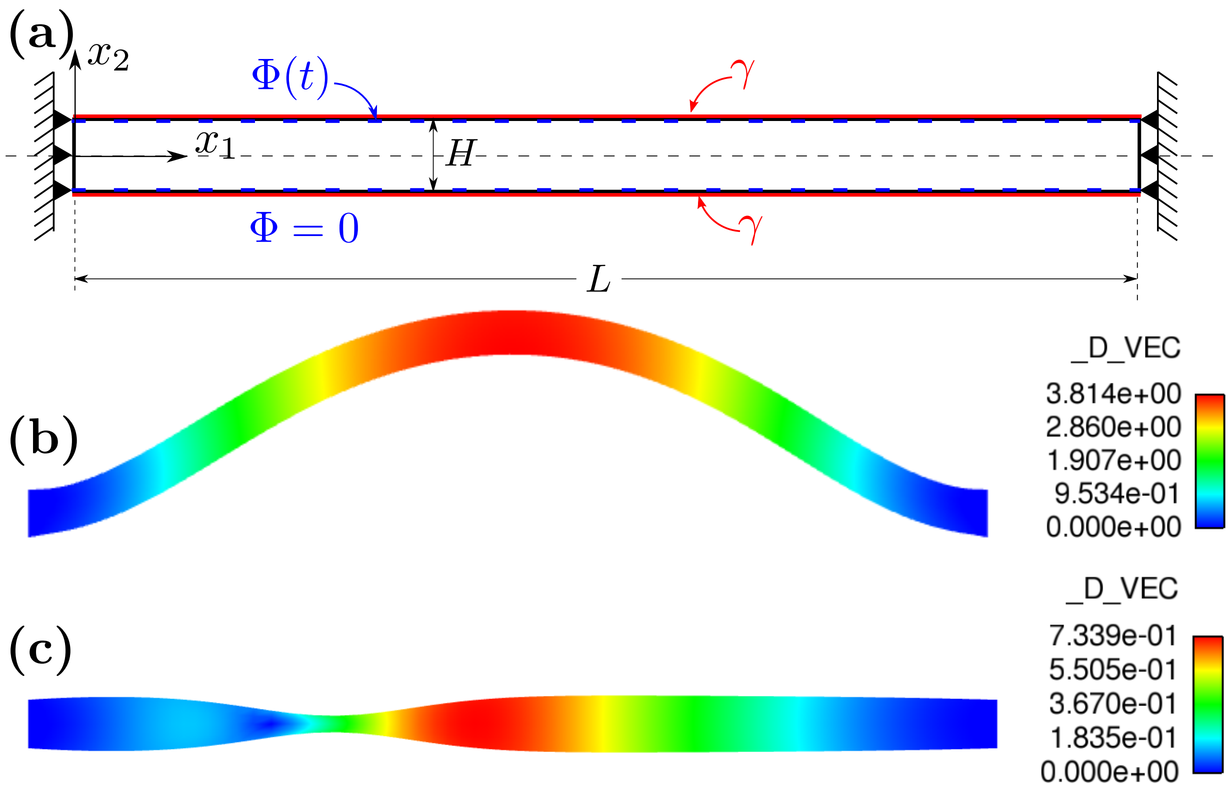

Figure 4: (a) Schematic with boundary conditions for a DE films subjected to elastocapillary and electrical forces. (b and c) FE results showing different modes of instability. (b) Buckling for normalized elastocapillary number of 0.5 when the critical voltage reaches 1.066. (c) Rayleigh-Plateau instability for normalized elastocapillary number of 5 when the critical voltage reaches 2.03. D_VEC refers to the displacement magnitude.

- Found that the electro-elastocapillary instability transitions from buckling (shown in Figure 4(b)) to Rayleigh-Plateau (shown in Figure 4(c)) at a critical normalized elastocapillary number of 2, as shown in Figure 5.

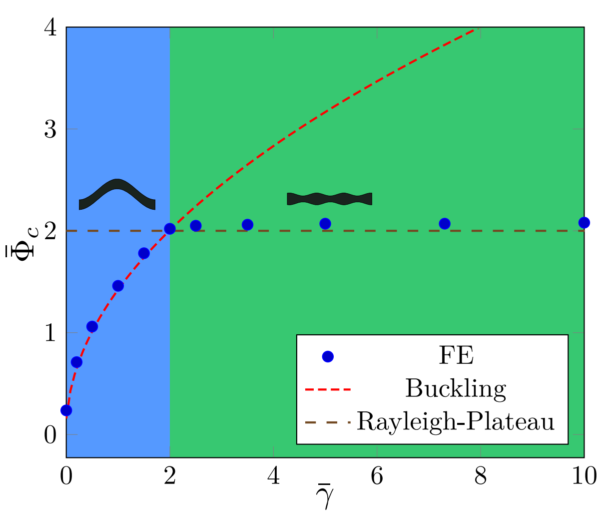

Figure 5: Homogeneous deformation of a DE subject to voltage loading for different elastocapillary numbers.

- Uncovered the fact that the lowest order instability wavelength is an infinite wavelength, while finite wavelength Rayleigh-Plateau instability is observed for larger critical voltages.

- One of the key challenges in modeling the nonlinear dynamical behavior of DEs is that all computational techniques to solve the coupled electromechanical system of equations for this class of materials have universally centered around a fully coupled monolithic formulation, in which the mechanical and electrostatic equations are solved simultaneously. Such monolithic formulations are accurate, but require significant computational expense, which has significantly hindered the ability to solve large scale, fully three-dimensional problems involving complex deformations and electromechanical instabilities of DEs. During this period, we have provided the theoretical basis for the effectiveness and accuracy of staggered explicit-implicit finite element formulations for DEs, where the mechanical and electrostatic equations are solved separately, while demonstrating the simplicity of the resulting staggered formulation. We have demonstrated the stability and accuracy of the staggered approach by solving complex electromechanically coupled problems involving electroactive polymers, where we focused on problems involving electromechanical instabilities such as creasing, wrinkling, and bursting drops. In all examples, effectively identical results to the fully monolithic solution are obtained, showing the accuracy of the staggered approach at a significantly reduced computational cost, as illustrated in Figures 6 and 7 below.
- We anticipate this development will be critical in enabling ARL personnel to easily and efficiently adapt their simulation codes to perform large-scale structural analyses of the dynamic behavior of DEs.

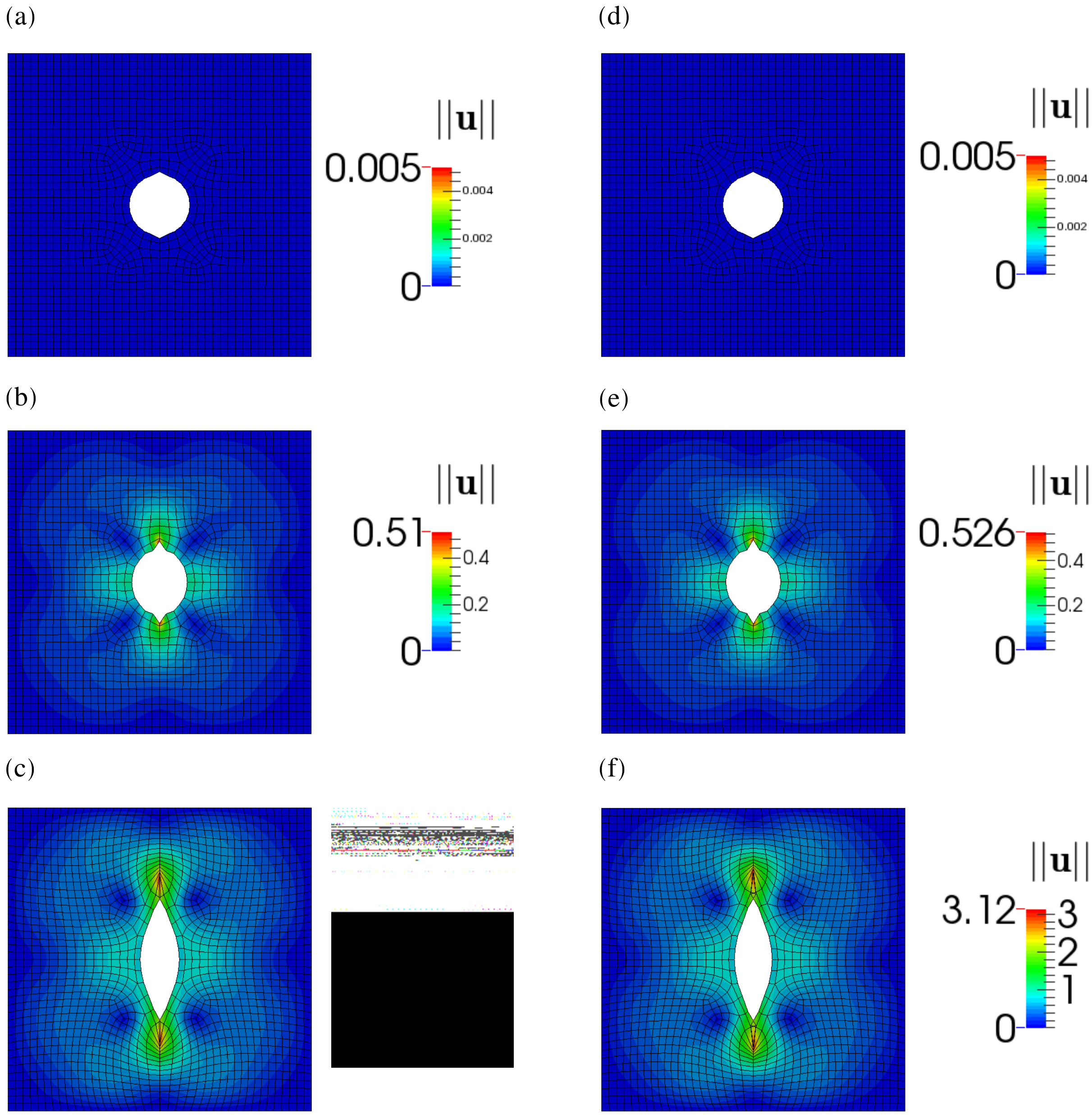

Figure 6: Fully coupled, monolithic solution on the left side (a)-(c) vs. staggered, explicit-implicit solution on the right side (d)-(f) for a bursting drop problem within a DE. ||u|| denotes the displacement magnitude.

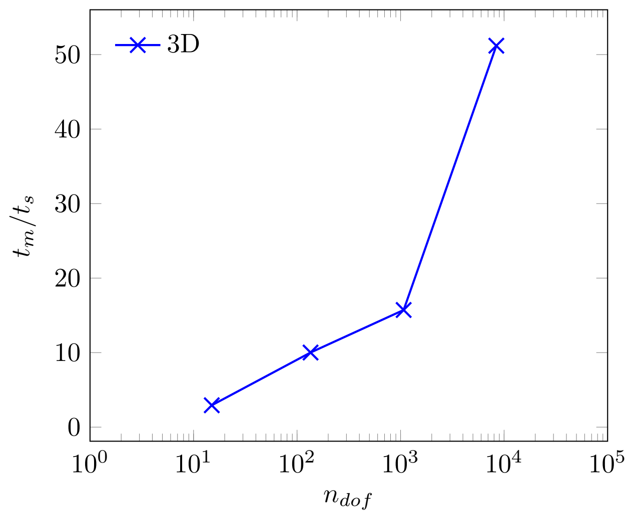

Figure 7: Ratio of elapsed time for monolithic model over elapsed time for staggered model (tm/ts) as a function of the total numbers of unconstrained degrees of freedom (ndof) for a 3D creasing problem. Note that the staggered method becomes significantly cheaper than the monolithic method once the number of degrees of freedom exceeds about 1000.

Collaborations and Technology Transfer

- With Prof. K.C. Park, University of Colorado, an expert in computational modeling techniques for coupled physics problems.

Resulting Journal Publications During Reporting Period

- S. Seifi and H.S. Park. "Computational Modeling of Electro-Elasto-Capillary Phenomena in Dielectric Elastomers", *International Journal of Solids and Structures* 2016; 87:236-244.
- S. Seifi and H.S. Park. "Electro-elastocapillary Rayleigh-Plateau Instability in Dielecric Elastomer Films", *Soft Matter* 2017; 13:4305-4310.
- B. Osmani, S. Seifi, H.S. Park, V. Leung, T. Topper and B. Muller. "Nanomechanical Probing of Thin-Film Dielectric Elastomer Transducers", *Applied Physics Letters* 2017; 111:093104.
- S. Seifi, K.C. Park and H.S. Park. "A Staggered Explicit-Implicit Finite Element Formulation for Electroactive Polymers", submitted to *Computer Methods in Applied Mechanics and Engineering* 2017.

Graduate Students Involved During Reporting Period

- Mr. Saman Seifi, who began as a PhD student on this project starting January, 2015

Honors

- The PI (Park) was awarded the International Association for Computational Mechanics (IACM) John Argyris Award for Young Scientists in March 2016. This award is given once every two years to a single investigator 40 years or younger, and recognizes outstanding accomplishments, particularly outstanding published papers.
- PI Harold Park was named an ASME (American Society of Mechanical Engineers) Fellow for the class of 2016